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RESISTOJET THRUSTER SHIELD EVALUATION



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NOMENCLATURE

d	Pitot probe diameter
K	Constant, Eq. (2)
\dot{m}	QCM mass change per unit time, thruster mass flow per unit time
$(\dot{m})_{max}$	QCM mass change per unit time with probe aligned to velocity vector
$(\dot{m})_{90}$	QCM mass change per unit time with probe at 90 deg to thruster axis
M_∞	Free-stream Mach number
P_0	Line pressure at thruster
Re_{2d}	Probe Reynolds number, $p_\infty U_\infty d/\mu_2$
T	Temperature
U_∞	Free-stream velocity
	Ratio of specific heats
θ	Angle to thruster axis
μ	Viscosity
ρ	Density
Subscripts	
2	Downstream of normal shock
∞	Free-stream static

1.0 INTRODUCTION

The work reported herein was performed by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Program Element 921E06, Control Number, 9E06, at the request of the NASA-Lewis Research Center (NASA LeRC). The NASA LeRC Project Manager was L. M. Zana. The results were obtained by Calspan Corporation/AEDC Division, operating contractor for the Aerospace Flight Dynamics Testing effort at AEDC, AFSC, Arnold Air Force Base, Tennessee. The testing was performed in the 4 x 10-ft Research Vacuum Chamber (RVC) of the von Karman Gas Dynamics Facility (VGF) during the period from April 30, 1987 through July 21, 1987, under AEDC Project Number CI63VV and Calspan Project Number V41V-17.

The resistojet thruster plume shield evaluation program was planned by NASA LeRC personnel to determine, 1) the magnitude of the mass flux into the region upstream of the nozzle exit plane, and 2) whether an appropriate shield could be developed to minimize the flow of nozzle gases into this region. The operational characteristics of the thruster required for this evaluation were specified by NASA LeRC. In order to accomplish the objectives of the test program, a rotary pitot pressure probe and a rotary, LN₂ cooled, Quartz Crystal Microbalance (QCM) were installed in the 4 by 10 ft (RVC).

Experimental data obtained from this test program were transmitted to NASA LeRC during the course of the test program, together with pertinent facility information necessary for the proper interpretation of the data. This report documents the planning and preparatory efforts required to support the test program.

2.0 APPARATUS

2.1 TEST FACILITY

The Research Vacuum Chamber, Fig. 1, is a stainless steel cylindrical vacuum chamber.

2.2 TEST ARTICLE

A multipropellant resistojet (Fig. 2) has been selected as a low-thrust option for the Space Station System. It is planned to use this system to dispose of a variety of excess fluids that are expected to be present on the space station and to use the thrust developed in this process for drag make up. It has been concluded (Ref. 1), that the use of these excess fluids in this manner will result in a reduction in Space Transportation System costs which would be associated with launching of the necessary propellants as well as the removal of the excess fluids from the space station. The performance characteristics of an engineering model of the multipropellant resistojet using hydrogen, helium, methane, water, nitrogen, air, argon and carbon dioxide, has been determined in Ref. 1 from thrust measurements made in a vacuum chamber at NASA LeRC.

A review of the design details of this thruster is given in Ref. 1 and is included here for convenience.

"The material used for construction of the engineering model thruster was grain-stabilized platinum because it exhibits long-term, high-temperature compatibility with a wide variety of oxidizing and reducing fluids. The component parts of the heat exchanger were fabricated and assembled by Johnson-Matthey, and contained a small quantity (less than 1 percent) of zirconium oxide dispersant as a grain stabilizer to minimize grain growth which occurs when materials are held at high temperatures for extended periods of time (Ref. 2). Excessive grain growth leads to distortion and weakening of components, which is of special concern for the pressure vessel/heat exchanger of a resistojet."

"The engineering model multipropellant resistojet, shown in Fig. 2, consists of a central cylindrical heat exchanger inside a coiled sheathed heater. This assembly is surrounded by several layers of radiation shields and encased in a cylindrical shroud which serves as a mounting and support structure for the heat exchanger/heater/radiation shield assembly. The heat exchanger incorporates thick pressure vessel walls designed to resist stress rupture for a minimum of 10,000 hrs at temperatures and internal pressures of interest. Table I summarizes the design features of the engineering model thruster."

"The heat exchanger shell is cylindrical with a series of semicircular grooves machined into the downstream half of the outer surface which retains the coiled sheathed heater, insuring proper location of the heater and providing a large surface area for conduction from the heater to the heat exchanger. The pressure vessel contains a hollow core cylinder, sealed at the downstream end, designed to force the incoming propellant through a series of 36 axial channels between the outer core surface and the inner heat exchanger surface. The core is present only in the upstream half of the heat exchanger due to difficulties encountered during assembly of the unit tested, which was the first engineering model produced. The design of the heat exchanger/core interface has been successfully changed to eliminate such difficulties in subsequent iterations. The upstream end of the pressure vessel contains a flange which incorporates the propellant inlet tube and the downstream end of the pressure vessel is terminated with a nozzle. The three pressure vessel components are joined by large-surface area diffusion bonds which serve as stress-bearing joints. The diffusion bonds are backed by electron beam welds to insure a positive gas seal. The diffusion bonds are used in relatively high-temperature, high-stress locations, since this joining technique does not destroy the grain stabilization, as does electron beam welding. The heater employed was manufactured by Englehard Industries, and consists of a rugged 1.6 mm diameter platinum rhodium center conductor surrounded by a layer of magnesium oxide insulator, all of which is contained within a grain-stabilized platinum sheath. This assembly is processed by swaging to compact the magnesia insulator between the sheath and center conductor, insuring proper centering of the center conductor within the sheath and eliminating any possibility of heater failure due to shorting. The heater is wound in a double

helix configuration which allows both power leads to be located in the cool upstream end of the thruster, enhancing the reliability of the heater termination assembly."

As a part of the performance evaluation described in Ref. 1 the temperature distribution within the thruster under steady-state conditions was measured. This information was necessary in order that the safe operating limits of this design could be defined without risking failure of any of the thruster components as a result of overheating. In order to make these measurements it was necessary to cut holes in the containment shroud at three locations: 1) near the nozzle, 2) at the center of the heat exchanger, and 3) near the propellant inlet. The placement of thermocouples positioned at these three locations is identified in Fig. 3. Also shown in Fig. 3 are the maximum temperatures that were measured at these locations for the conditions of the present investigation.

A schematic of the gas addition system is presented in Fig. 4. The flow of gas through the resistojet was measured with Fischer & Porter and Matheson flow meters.

2.3 TEST INSTRUMENTATION

2.3.1 Pitot Pressure Measurements

For high Reynolds number flows, i.e. $Re_{2d} > 300$, a knowledge of the pitot pressure, together with either the static or reservoir pressure, is sufficient to determine the flow Mach number, provided the gas can be treated as a perfect gas and the change in flow properties across the probe bow shock is adequately defined by the Rankine-Hugoniot relations. For flows that meet these requirements, the pitot probe is a simple and effective diagnostic technique. In its simplest form, the pitot probe consists of nothing more than a flat-faced, open-ended tube aligned parallel to the flow, with the open end facing the oncoming gas flow and the other end connected to a pressure transducer. The probe can be sized according to (1) the requirements of the flow field under investigation and (2) the required response time for the measurement which is in turn dependent upon the physical characteristics of the probe and the pressure transducer.

2.3.2 Quartz Crystal Microbalance

When a piezoelectric crystal, vibrating at its resonant frequency, experiences a deposition of mass on its exposed surface, there is a readily observable change in crystal frequency. Theoretical and experimental evaluations of the quartz crystal microbalance (QCM) have shown that for a particular QCM configuration there is a well-defined relationship between the mass deposited and frequency change. The QCM's ability to measure accurately low levels of mass flux led to its use for such measurements in the far field of nozzle plumes in a hard vacuum, Ref. 3. Mass flux measurements in these tests (Ref. 3) were obtained using a number of QCM's located at fixed angles and radial

positions with respect to the nozzle exit. This arrangement of QCM's limited the amount of mass flux information that could be obtained for a particular nozzle test condition. It also required that each QCM be accurately calibrated such that any small differences between the performance characteristics of the individual QCM's were properly accounted for. Ideally, to make mass flux measurements in the plume of a nozzle expansion, a single cryogenically cooled QCM is required whose angular orientation and position with respect to the nozzle exit plane can be controlled. Changes in the position of the QCM with respect to the nozzle exit plane can be accomplished by positioning the QCM at a fixed location and moving the nozzle. The angular orientation of the QCM sensor surface with respect to the nozzle exit plane can be controlled by mounting the sensor on a motor-driven rotary positioning table.

3.0 TEST DESCRIPTION

3.1 TEST UNIT AND RESISTOJET OPERATING CONDITIONS

At the outset of this experimental investigation it was established by the sponsor that the resistojet would be evaluated using carbon dioxide as the propellant. In keeping with earlier performance evaluations (Ref. 1) a mass flow of 0.29 gm/sec and a heater power of 405 watts (at a current of 23 amp) were selected for use. At this operating condition measurements of the local mass flux and local velocity vector in the thruster plume upstream of the nozzle exit plane were required for the basic thruster and for as many plume shield configurations as possible within project constraints.

A photograph of the thruster in the as received condition is shown in Fig. 5. This photograph shows the positions of the NASA/LeRC installed Chromel®-Alumel® thermocouples that are used to monitor the internal performance of the thruster heater. A photograph of the resistojet installed in the RVC is shown in Fig. 6.

To provide the chamber operating conditions required by this test matrix, consistent and accurate measurements of pressure and mass flow were required.

The specification for the carbon dioxide used in the present experimental program was CO₂ min. 99.5 percent, N₂ max. 0.342 percent, O₂ max. 0.086 percent, and H₂O max. 0.072 percent. All of the gas used in this program was analyzed prior to use and was found to meet the above specification.

Depending upon the requirements of the test, it was found that a period of time on the order of 2 to 3 hours was required to bring the chamber and thruster to the desired operating conditions, i.e., thruster temperature, gas temperature, and cryoliner temperature. Sufficient temperature and pressure instrumentation was available to monitor the performance of the complete chamber/test article configuration. This information was continuously presented on a video display terminal, and a printout was obtainable at any of a wide variety of selectable frequencies (determined primarily by the requirements of the test).

3.2 DIAGNOSTIC MEASUREMENTS

The pitot and QCM probes were accurately positioned both axially and radially with respect to the nozzle exit plane prior to chamber pump down. It was not possible to detect any movement of the probe or nozzle as a result of chamber evacuation. However, as the chamber was cooled and the thruster heated, axial movement in the lip of the nozzle was observed.

An accurate measurement of this growth was determined by tracking the nozzle axially until the lip was once again aligned with the probe. This correction was made for all test conditions. Although it was not possible to measure the radial growth of the nozzle, it was determined from complete radial surveys in the exit plane that the thruster axis did not move radially as the thruster was heated.

The movement of the thruster and probe could be controlled either wholly with the computer, wholly manually, or with a combination of both. The exact method of operation in any particular test sequence was determined by the requirements of that sequence.

3.3 FACTORS AFFECTING THE CONDUCT OF THE EXPERIMENT

There were some concerns with regard to the initial operation of the thruster in that although the thruster was operating at the required power and mass flow, the heater temperature was found to be approximately 70C less than had been observed at NASA LeRC (Ref. 1). In discussions with the sponsor it was agreed that differences of this magnitude were not significant and that they were probably attributable to differences in the thruster mounting configuration in the two test facilities.

3.4 ESTIMATE OF UNCERTAINTIES

The evaluation of the uncertainty in the basic pressure measurements is well defined since the absolute pressure transducers used in the present investigation are calibrated and compared with the base standard. Absolute pressure transducers used in the present study, cover the pressure range from 1×10^{-4} to 3×10^3 torr. A continuous record of the output of these gages was maintained such that gage-to-gage comparisons in regions of pressure overlap could be made. In this way, any change in gage performance could be determined and accounted for. Bayard-Alpert ion gages together with the Granville-Phillips Conveptron gages were also used for pressure measurements from 1×10^{-5} to 5×10^{-1} torr.

In the interpretation of any of the probe pressure measurements, account must be taken of the probe characteristics, e.g., temperature and Reynolds number, (since these variables can have an effect upon the

measured pressure), before any definitive interpretation of the measurement can be made.

Based on a previous experimental investigation where the QCM used in the present investigation was placed in a flow field where the local mass flux was known, the local mass flux measurements were shown to have an uncertainty of approximately 10 percent. Based on this information it has been concluded in the present investigation that this represents a reasonable measure of the uncertainty of the mass flux values.

4.0 DATA PACKAGE PRESENTATION

Tabulations and plots of the experimental measurements of total thruster run time, heater power settings, pitot pressure, local flow angle, chamber pressure, mass flow, gas inbleed line pressure, heater temperatures, ion gage probe pressure and local mass flux are contained in the data package that is associated with this report. Representative plots of some of the measurements that are contained in the data package are presented in Figs. 7-14.

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3. Chirivella, J. E., "Mass Flux Measurements and Correlations in The Backflow Region of a Nozzle Plume," AIAA Paper No. 73-731, Presented at Eighth Thermophysics Conference, Palm Springs, California, July 16-18, 1973.

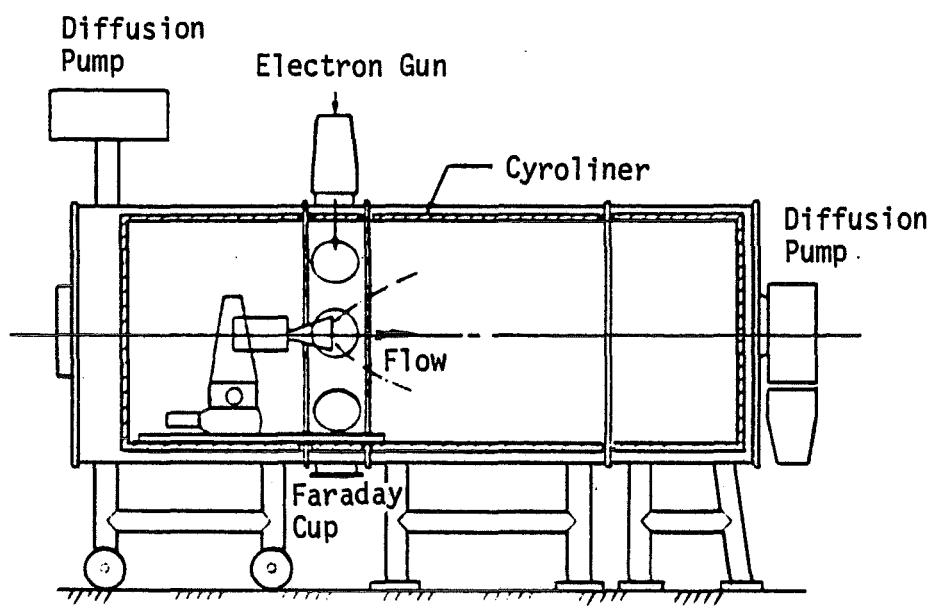


Figure 1. Schematic of the 4-by 10-ft Research Vacuum Chamber

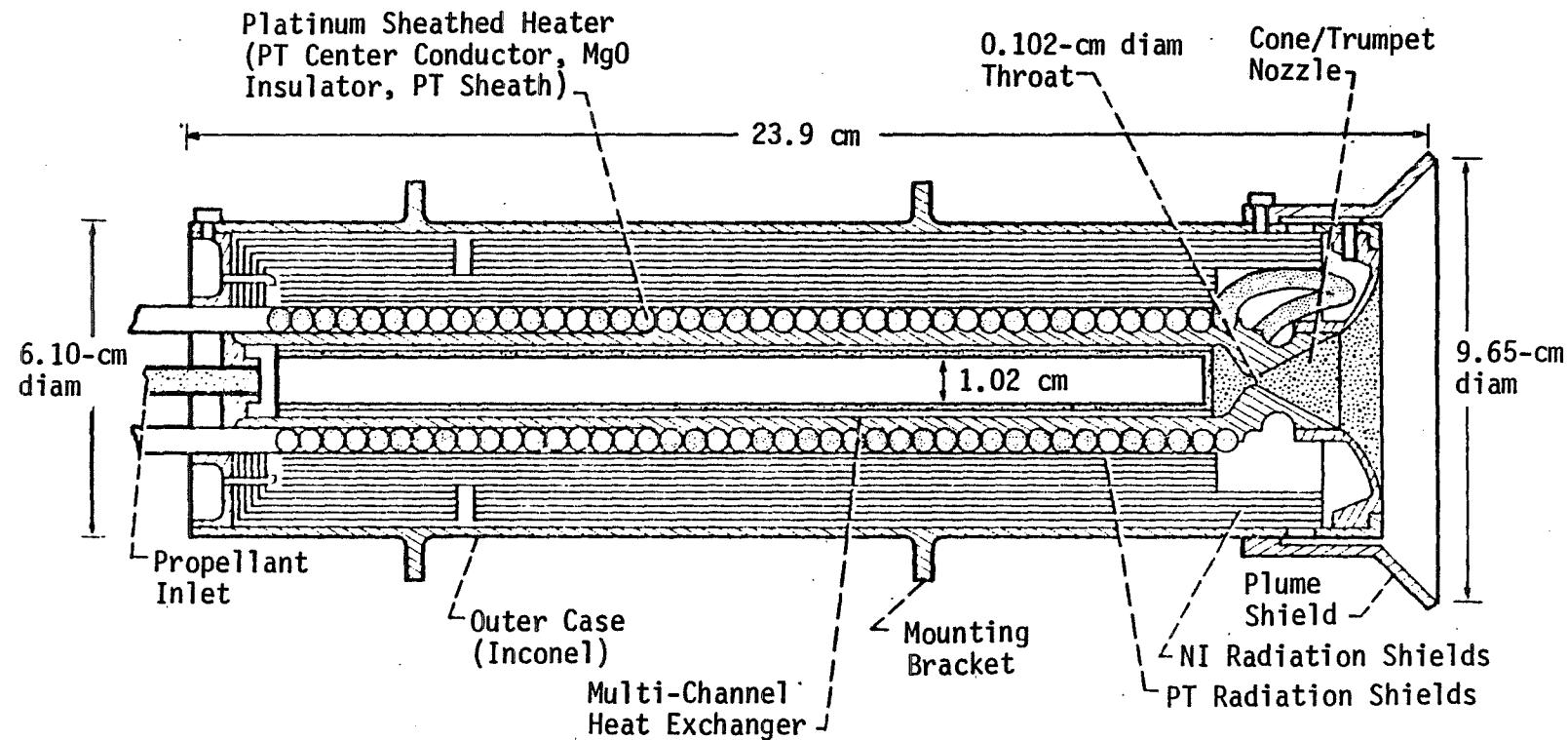
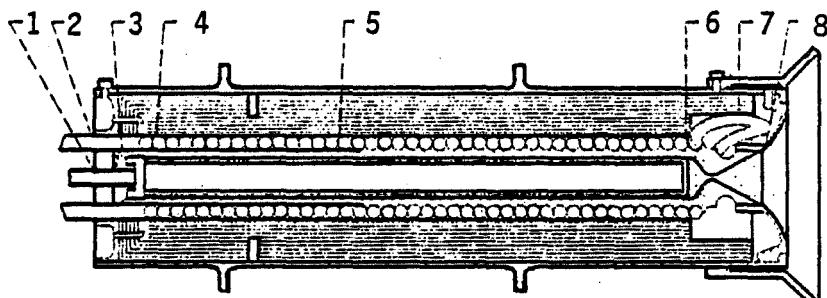


Figure 2. Advanced Development Engineering Model Resistojet



<u>Thermocouple Reference Number</u>	<u>Temperature, °C</u>	Carbon Dioxide Pressure, 2,030 torr Mass Flow, 0.29, gm/sec Power, 405 watts Current, 23 amp
1	426	
2	560	
3	557	
4	630	
5	805	
6	879	
7	842	
8	743	

Figure 3. Engineering Model Thruster Temperature Profile

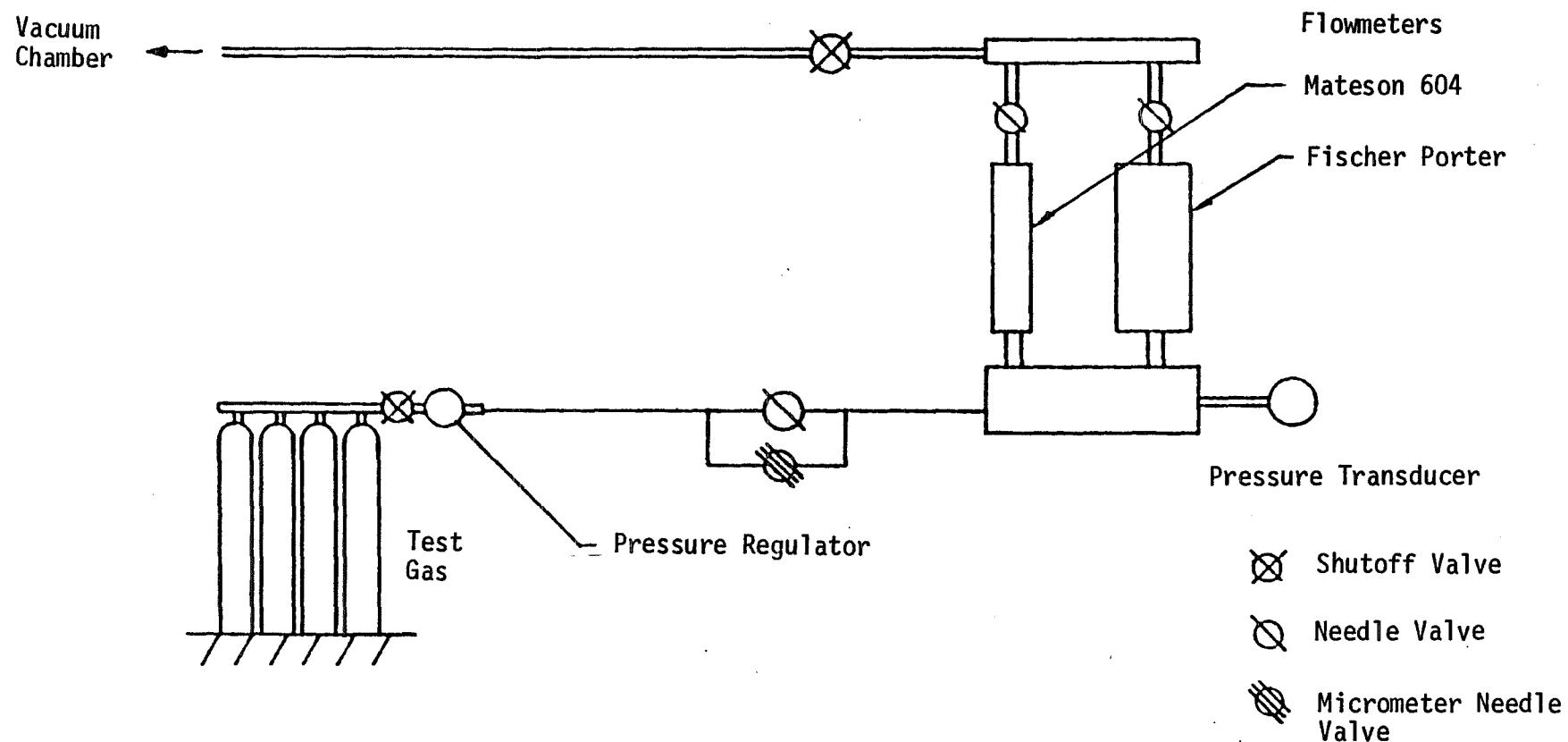
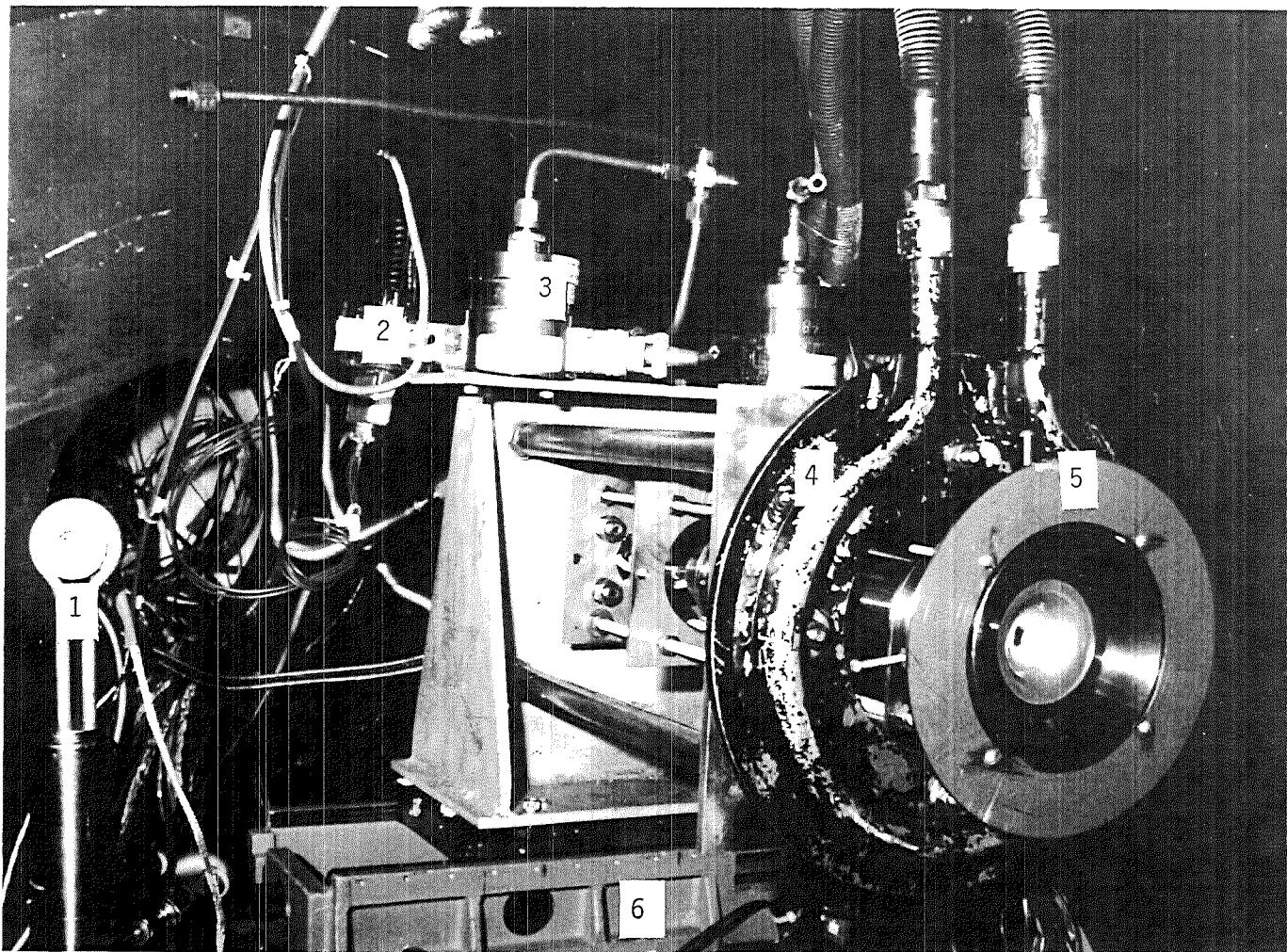


Figure 4. Schematic of Gas Addition System

Figure 5. Photograph of Resistojet



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- 1. QCM
- 2. Nude Ion Gage
- 3. Pressure Transducer
- 4. Cryo-Cooled Plate
- 5. Exit Plane Plume Shield
- 6. Traverse Table

Figure 6. Resistojet Installed in the Research Vacuum Chamber

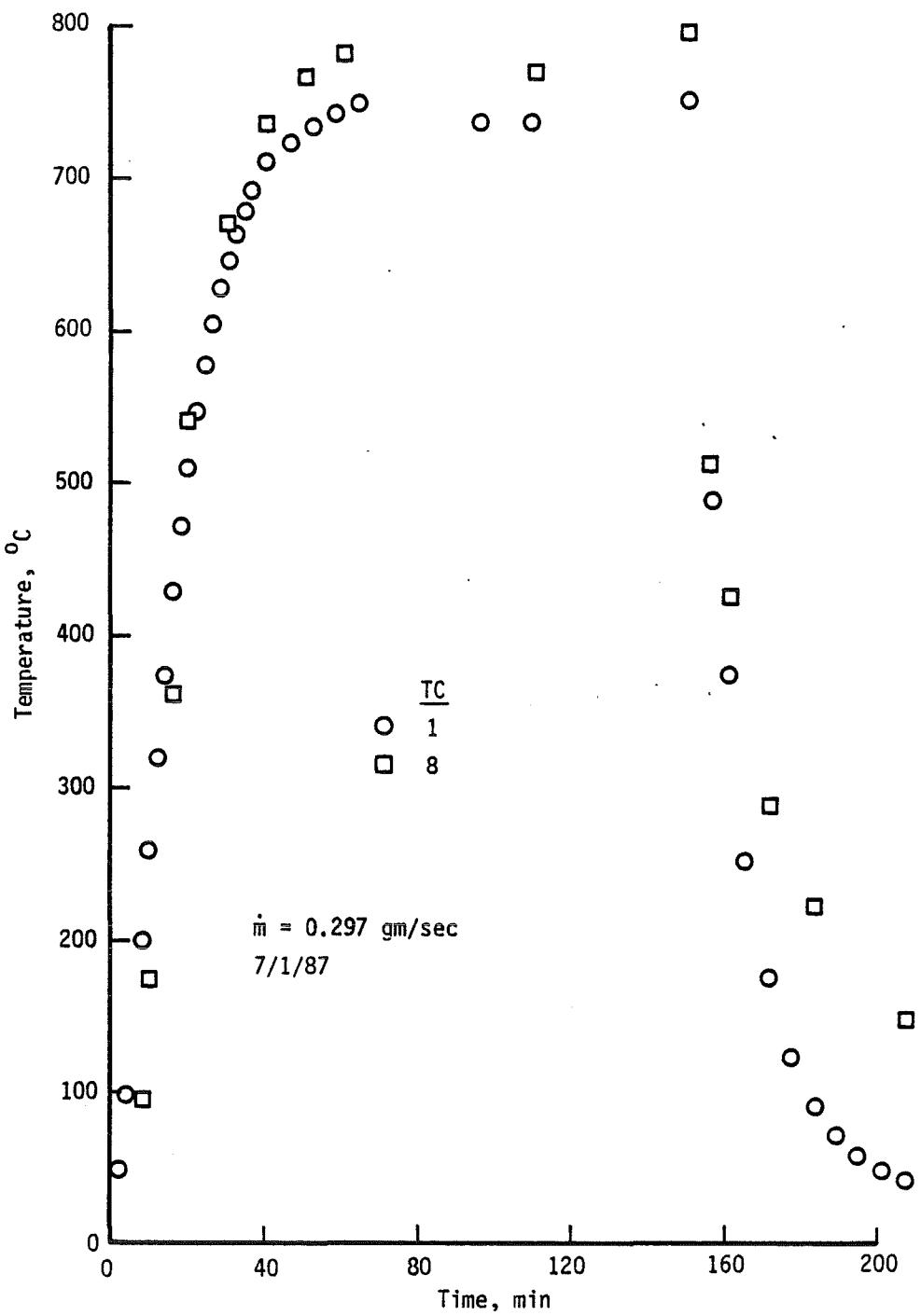


Figure 7. Resistojet Warm Up and Cool Down Characteristics.

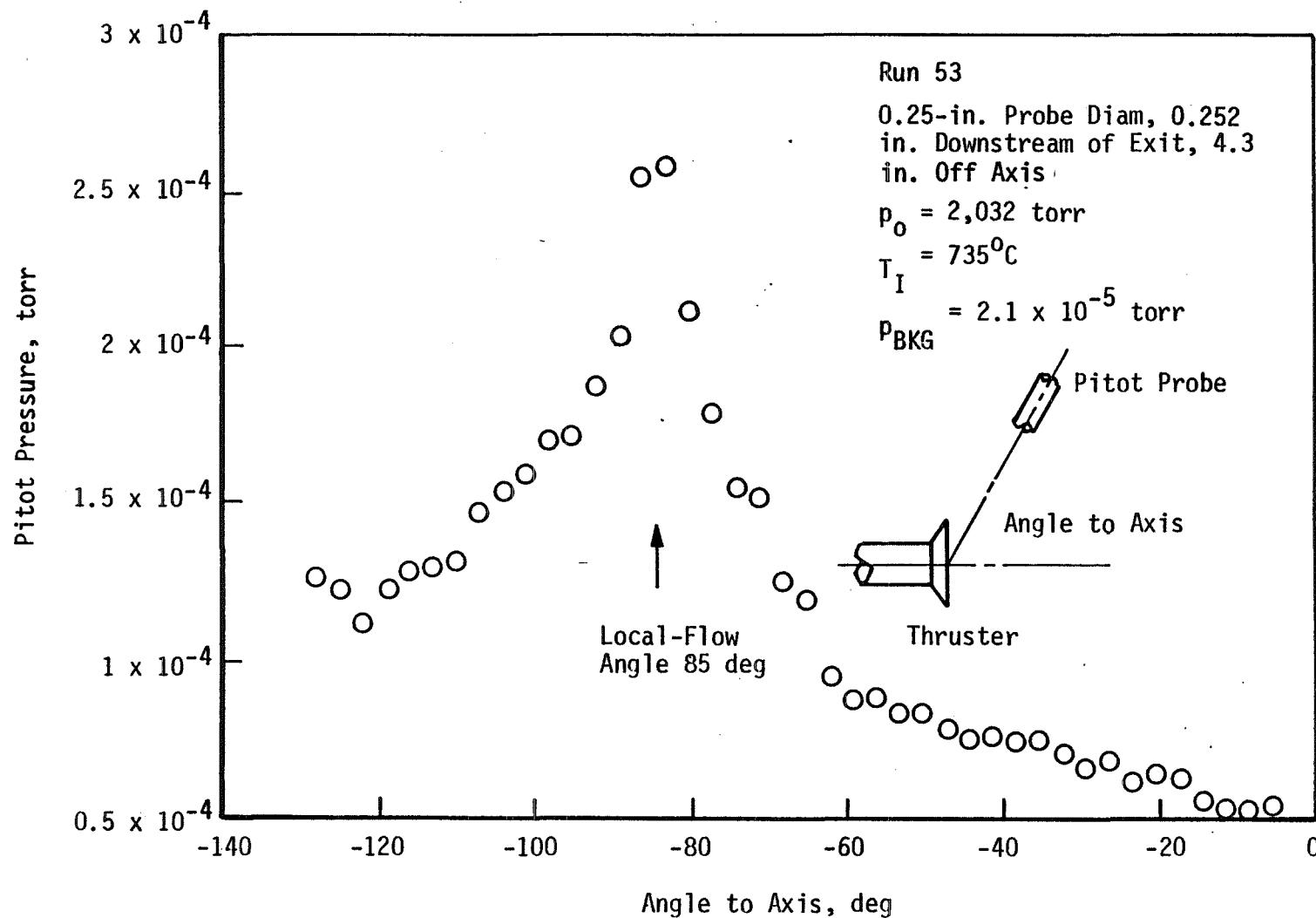


Figure 8. Variation of Pitot Pressure with Angle to Thruster Axis.

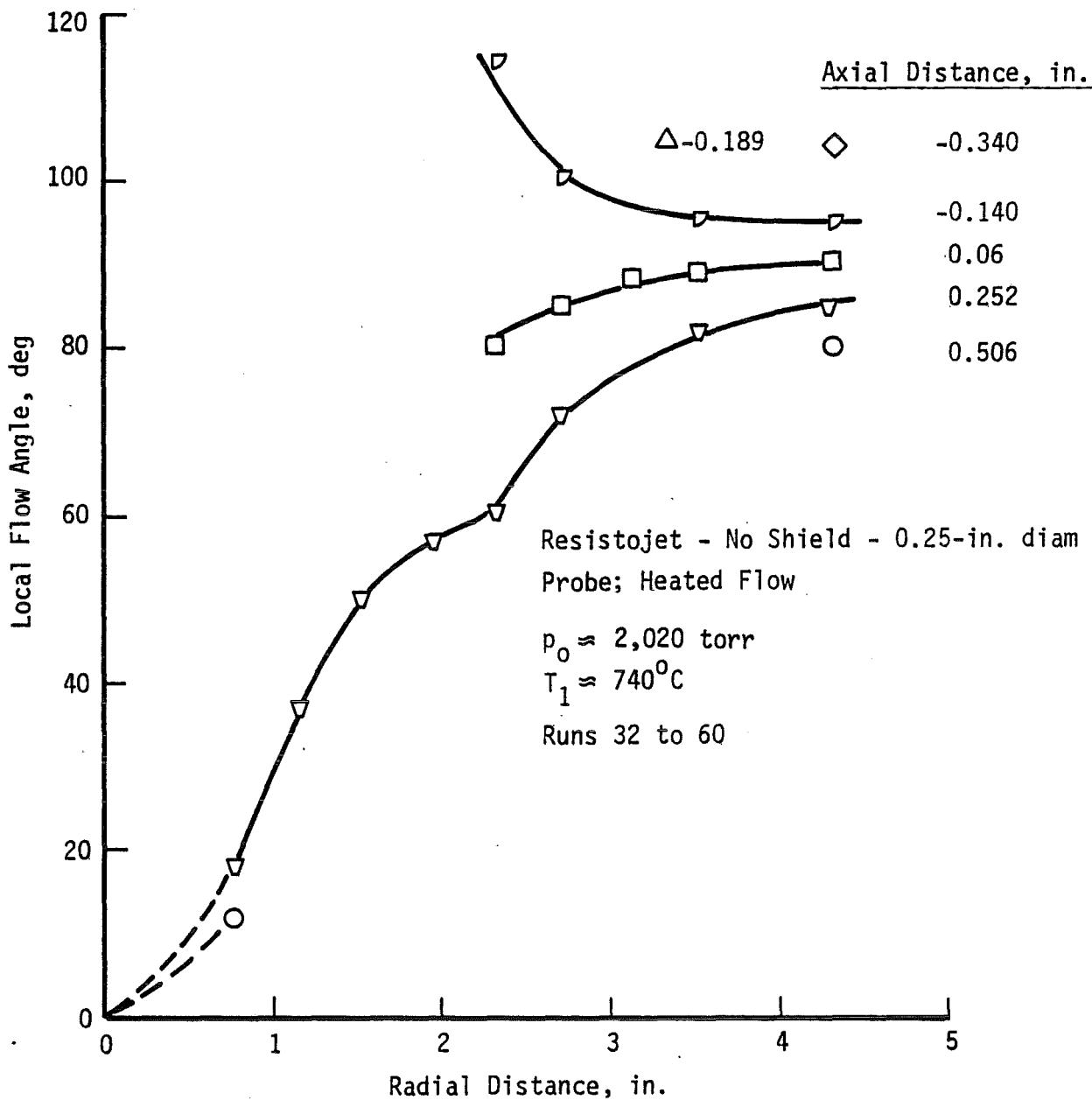


Figure 9. Resistojet - Local Flow Angle Variation with Axial and Radial Distance - No Shield

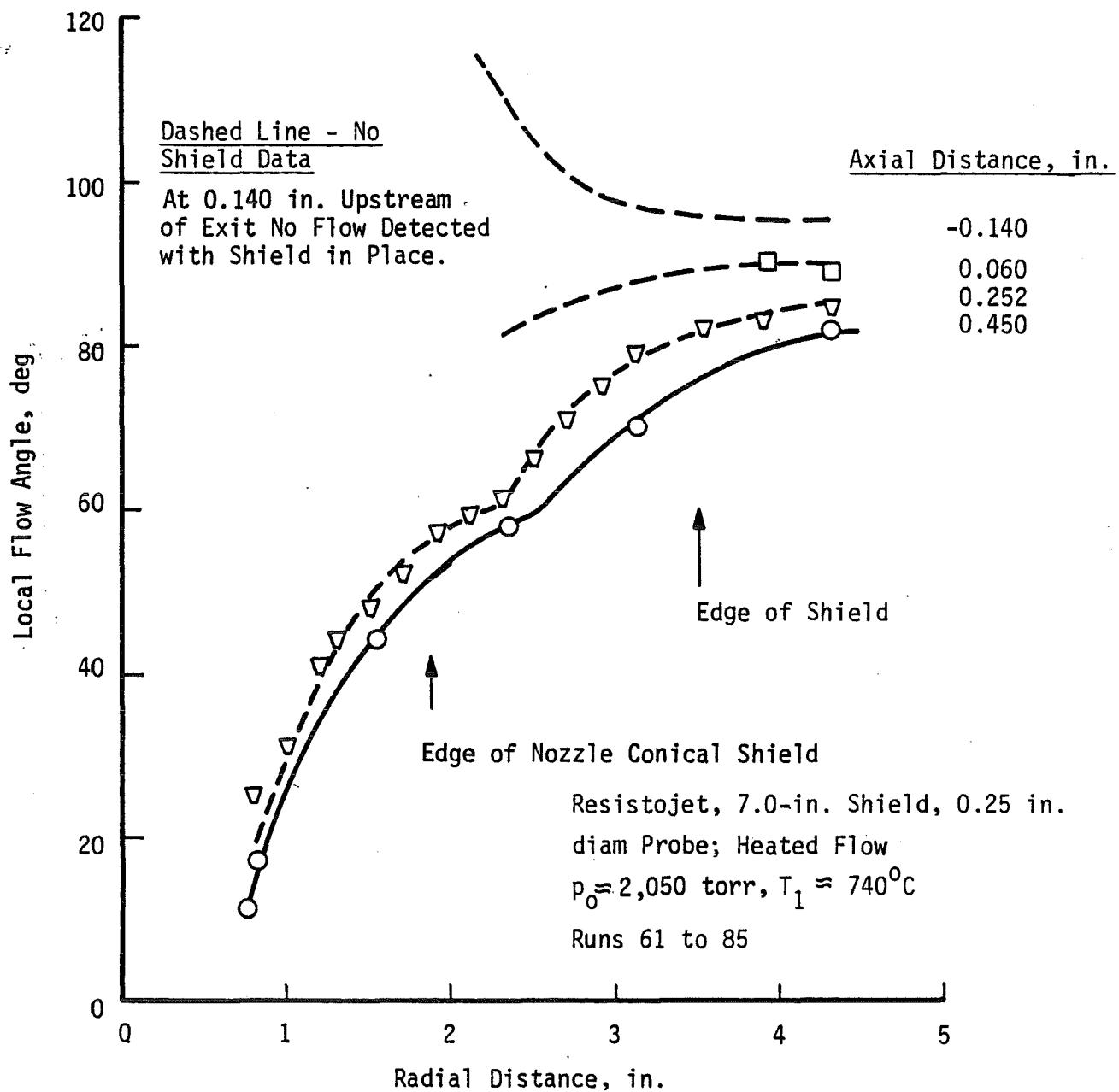


Figure 10. Resistojet - Local Flow Angle Variation with Axial and Radial Distance - 7.0 in. diam Shield

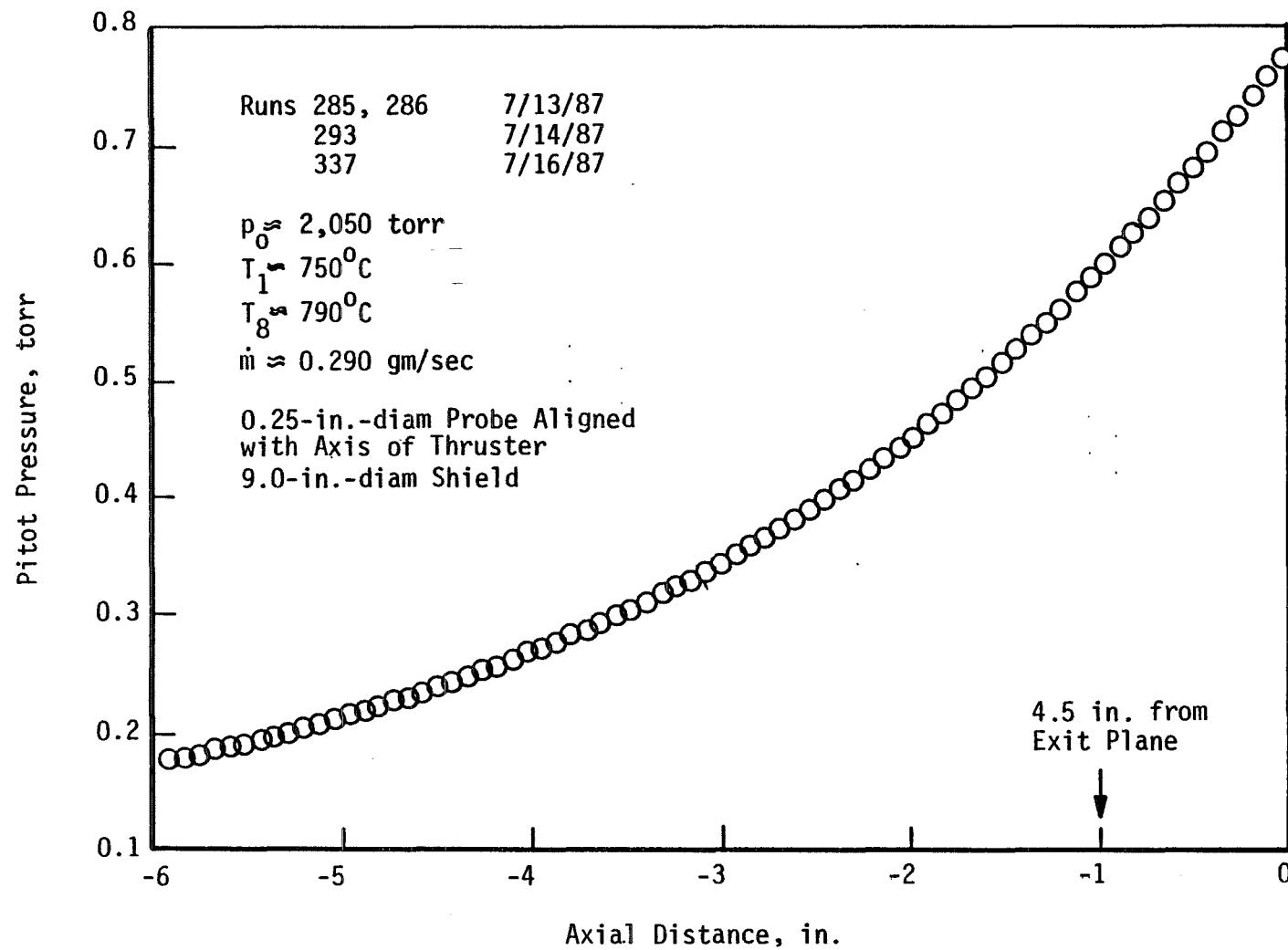


Figure 11. Day to Day Repeatability of Centerline Pitot Pressure Variation with Axial Position.

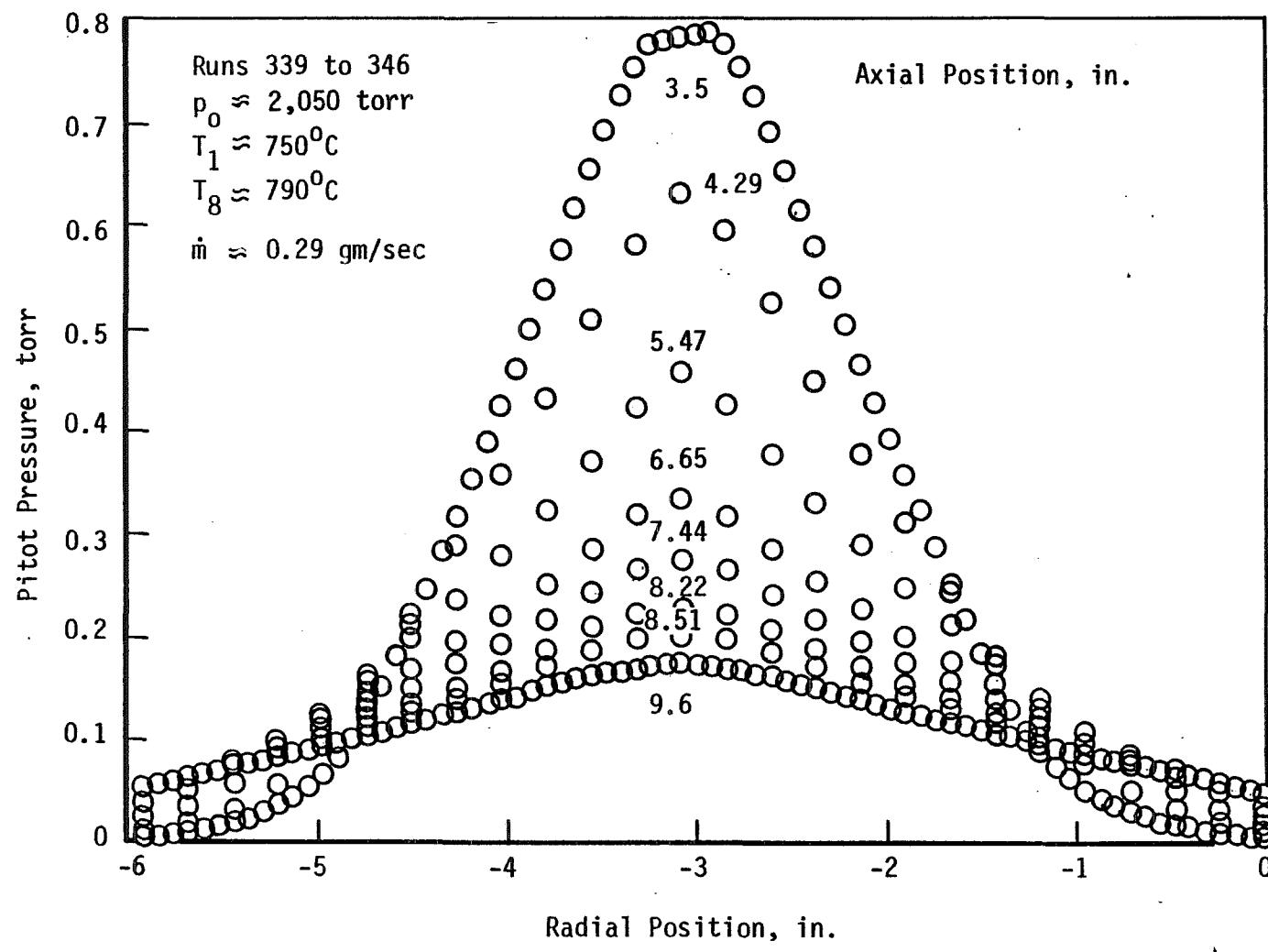


Figure 12. Radial Pitot Pressure Profiles at Various Axial Locations.

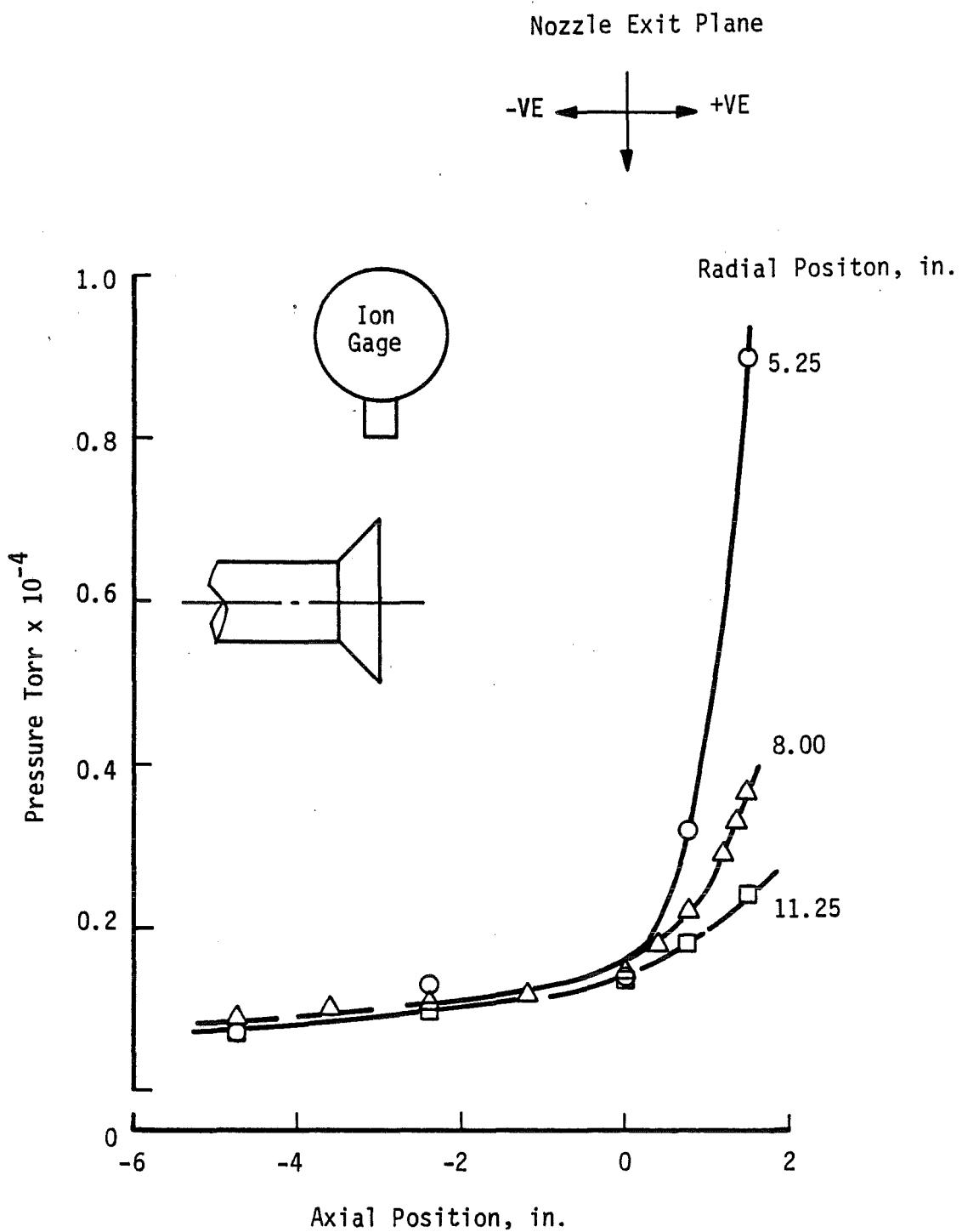


Figure 13. Pressure Variation with Axial and Radial Position for Gage Normal to Thruster Axis

Axial Position, in.	$(\dot{m})_{\text{max}}$ gm/sec	$(\theta)_{(\dot{m})\text{max}},$ deg	$(\dot{m})_{90}$ gm/sec
-2.5	1.10^{-7}	96	9.5^{-8}
-2.1	1.3^{-7}	140	---
-1.7	1.43^{-7}	136	9.3^{-8}
-1.3	1.50^{-7}	126	1.2^{-7}
-0.92	1.65^{-7}	128	1.35^{-7}
-0.52	1.60^{-7}	128	---
-0.12	1.90^{-7}	116	1.65^{-7}

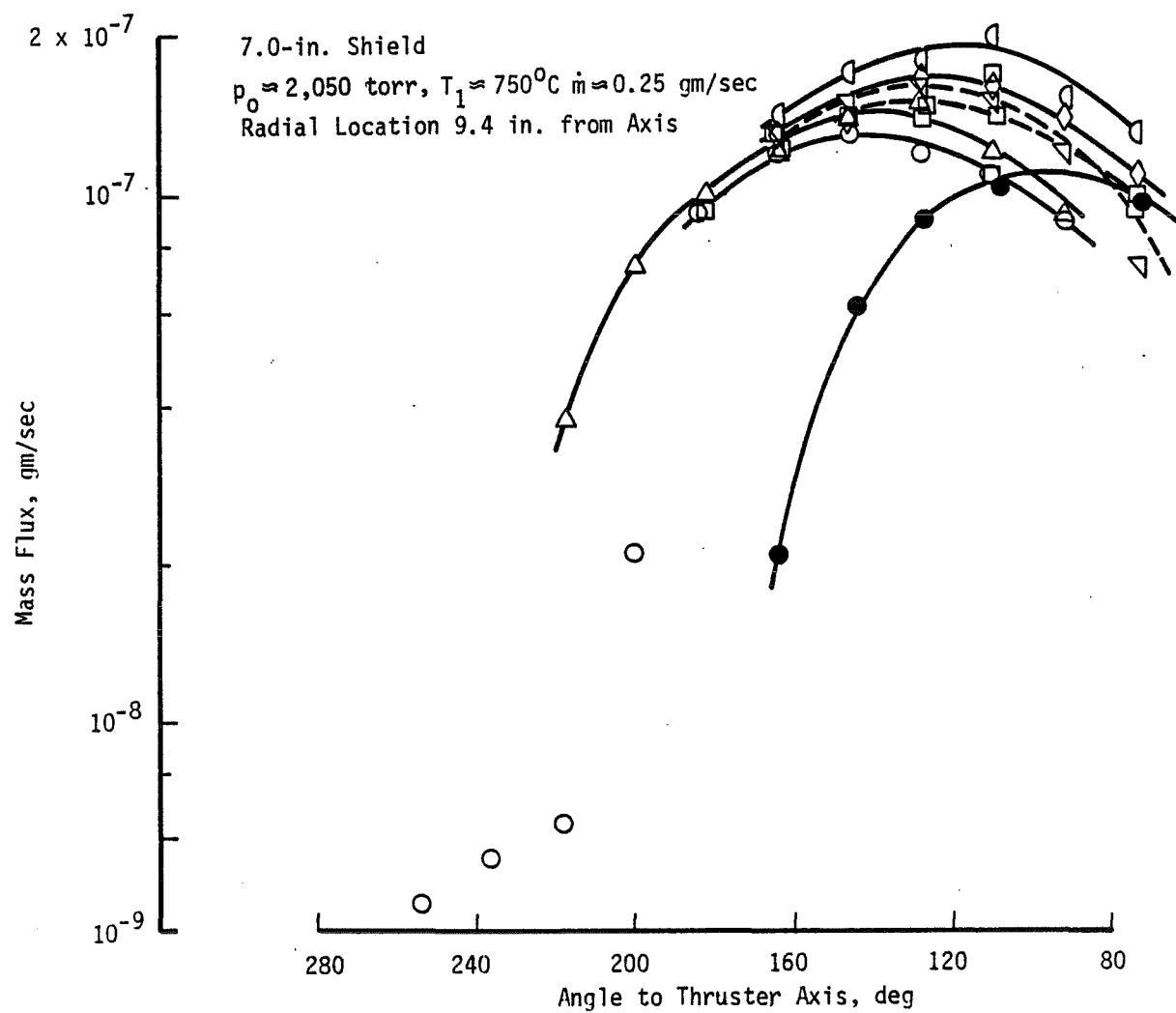


Figure 14. Variation of Mass Flux with Angle and Axial Position at a Fixed Radial Location

Table 1. Engineering Model Resistojet Design Characteristics Summary

<ul style="list-style-type: none">• Heater-coiled, sheathed<ul style="list-style-type: none">- Center conductor- Insulation- Sheath- Length• Heat exchanger<ul style="list-style-type: none">- Material- Flow path- Design chamber pressure• Thermal insulation• Outer shroud material• Maximum operating temperature (design)• Weight• Envelope	<p>Pt-10 percent Rh, 0.156 cm diameter MgO, 0.069 cm radial thickness Grain-stabilized Pt, 0.048 cm wall 3.3 m before coiling</p> <p>Grain-stabilized Pt 36 channels 0.05/cm wide x 0.127 cm deep x 10.2 cm long 0.1 to 0.3 MPa</p> <p>10 radiation shields - five 0.003 cm thick Pt - five 0.010 cm thick Ni</p> <p>Inconel</p> <p>1400 °C</p> <p>3.6 kg</p> <p>24.1 cm long x 10.2 cm diameter</p>
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